THE PHYTOPLANKTON OF GREAT POND, MASSACHUSETTS [1]

E. M. HULBURT

Hydrographic Office, Navy Department, Washington, D. C.

Although the plankton flora of moderately deep estuaries has been studied to some degree (Braarud and Bursa, 1939; Cowles, 1930; Gran and Braarud, 1935; Lohmann, 1908; Morse, 1947) very little quantitative study of phytoplankton in very shallow estuaries has been done. Several investigators in Belgium and Holland (Conrad, 1926a, 1926b; Massart, 1920; Van Goor, 1925a, 1925b, 1925c) have studied taxonomically the phytoplankton of very shoal estuaries. The forms they describe are almost entirely flagellates. It would be of great interest to learn whether these taxonomic studies indicate a distinctly different flora composed primarily of flagellates or whether diatoms, as well as flagellates, thrive in very shallow estuaries. Further, in the event that flagellates should dominate in shoal estuaries, it would be of interest to characterize the conditions associated with their dominance.

The Embayment Investigated

Figure 1 shows the form and depth of Great Pond. A narrow gut admits water from Vineyard Sound at one end and a small river, the Coonamessett, empties at the other end. It is divided into a wider seaward portion, the main pond, and a narrower landward portion, the arm. Its depth is nowhere greater than 9 feet at highest high tide. The hydrography of the Pond has been well studied by Barlow (in press), but a few of the salient features are reviewed here. The mean salinity indicates that the Pond water is 83 parts sea water and 17 parts river water. Surface salinity decreases from 32‰ in the Sound to 1–2‰ near the mouth of the River. Bottom salinity decreases from 32‰ to 24‰ near the mouth of the River, indicating marked stratification in the arm. The effect of wind blowing toward the Sound is to move the surface water seaward, resulting in upwelling of deep water and increase of surface salinities to 24‰ or above all the way to the River.

Water samples were taken at the stations indicated in Figure 1 from the shore in February and March and from a rowboat during the rest of the year. Samples were taken within several inches of the surface and approximately ten inches from the bottom. Phytoplankton cell counts and phosphate, turbidity, and salinity determinations were made on each sample.

Methods

Cell counts were made from four to forty-eight hours after samples were collected. Cell concentrations were determined by counting living cells in a very shallow chamber, so that a high power microscope objective could be used. Usually the water sample was concentrated on a smooth-surfaced porcelain filter with a pore

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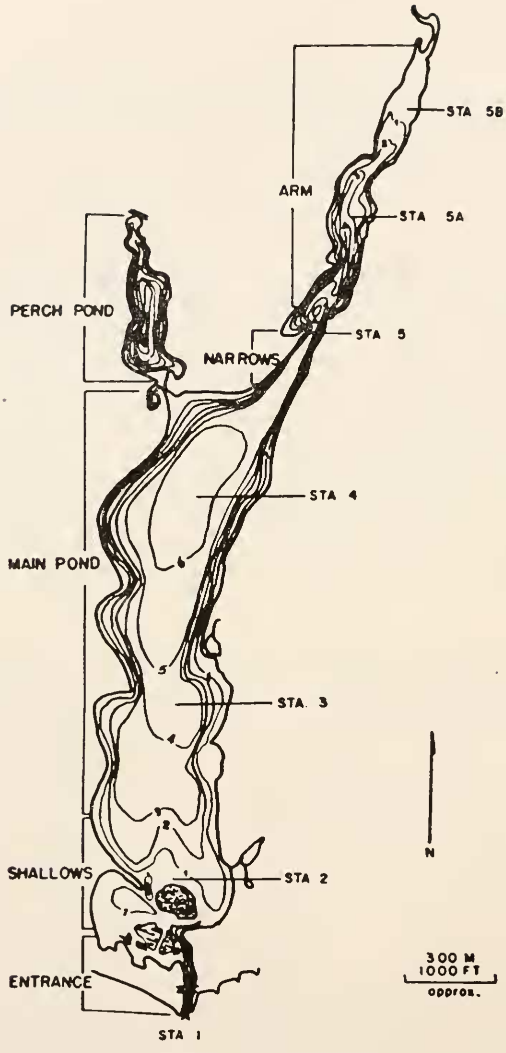

Figure 1. The morphometry of Great Pond. Depths are in feet.

diameter of 0.5 μ, manufactured by the Selas Corporation. Occasionally counts were made without filtration. Comparison of filtered and unfiltered counts showed that a large proportion of the cells was lost in filtration. Therefore, all filtered counts were multiplied by 1.81 to give the true concentration of cells in the water. All cells from 2–3 μ in diameter to about 50 μ in diameter were counted.

Results

Figure 2 shows the distribution of total phytoplankton. In the surface waters greater concentrations occurred within the Pond, and this difference was greater

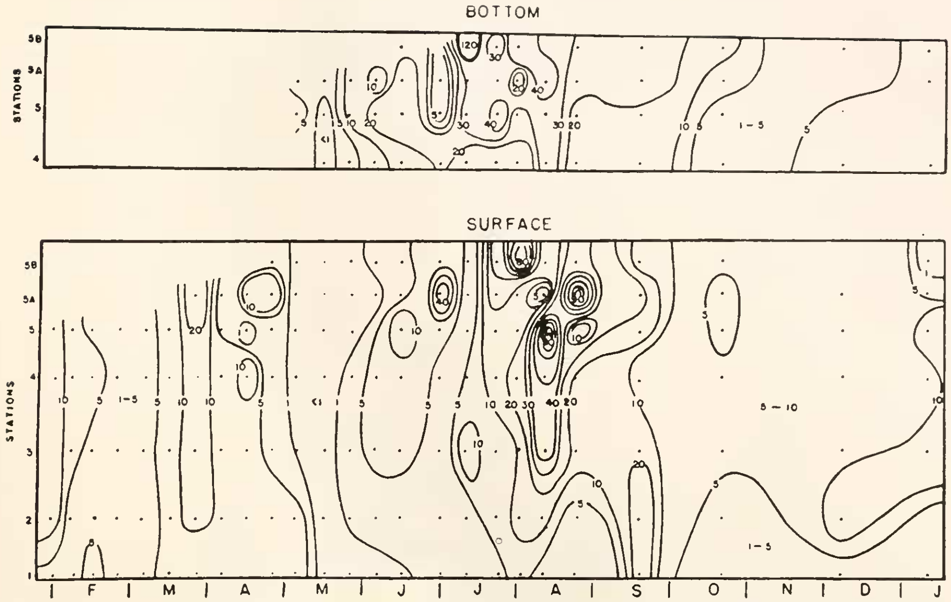

FIGURE 2. The distribution of total phytoplankton. Values × 10^6 are numbers of cells per liter.

during the summer than during the rest of the year. In summer there was, at a maximum, a 20-fold increase from the Sound to the surface waters of the arm. Between mid-September and the end of May, by contrast, the greatest increase from Sound to Pond was four-fold. The highest concentration in the surface waters, over 90,000,000 cells per liter, occurred in the summer at Station 5, well up the Pond. It is noteworthy that much greater fluctuations in cell concentrations occurred during summer than during the rest of the year. This feature was particu-

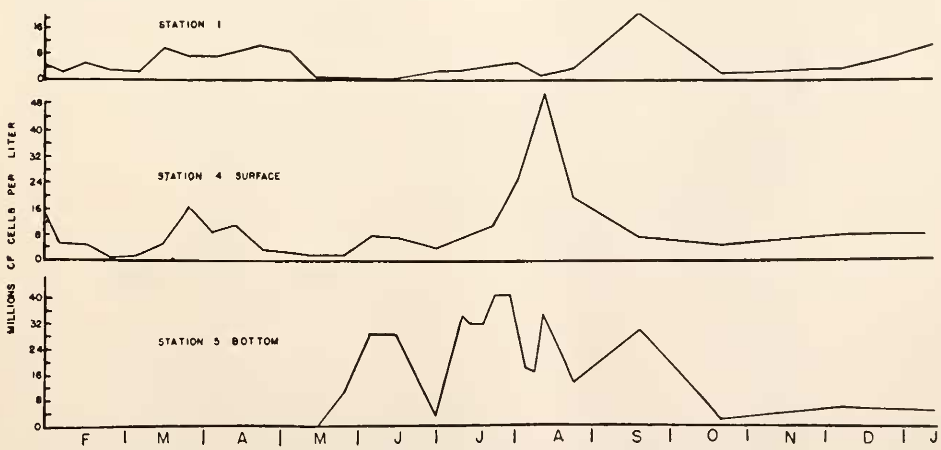

FIGURE 3. The seasonal cycle of total phytoplankton.

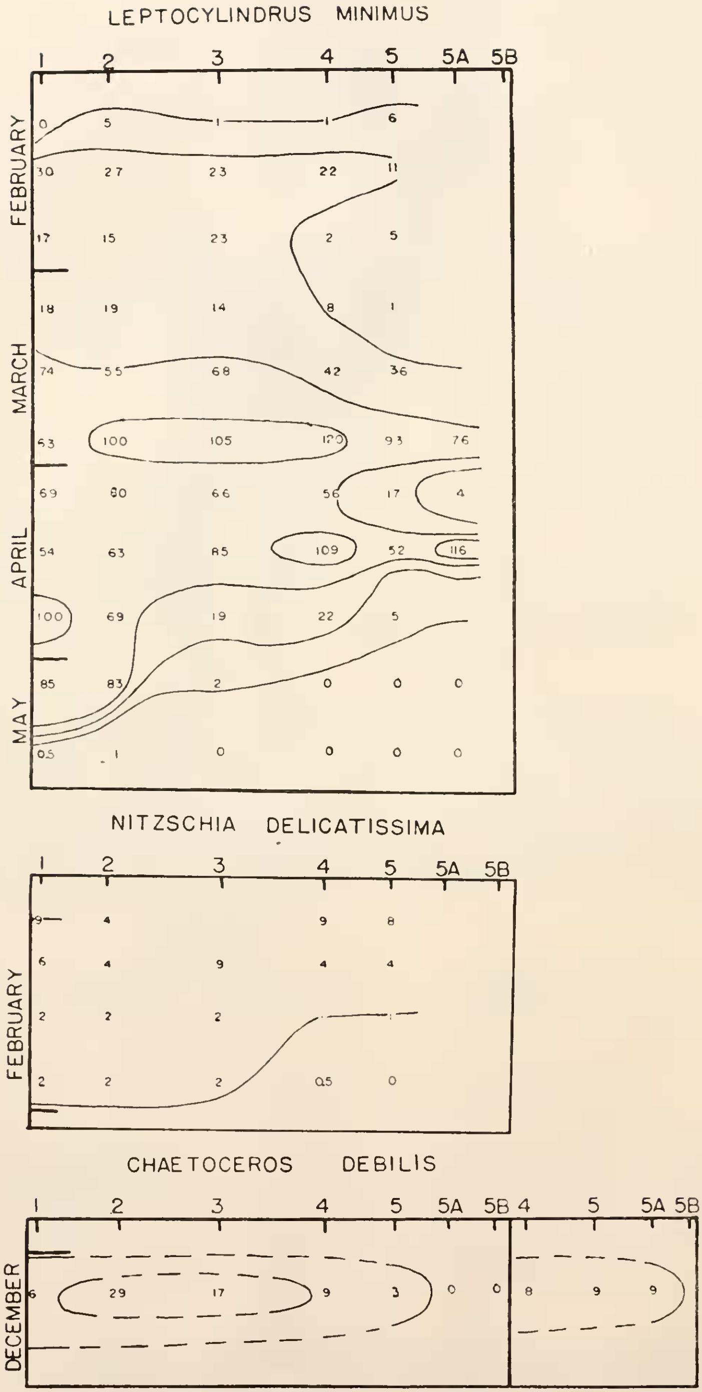

FIGURE 4. The distribution of Sound-derived species. Values $\times 10^5$ are numbers of cells per liter. Station numbers, 1–5b, cross the figure.

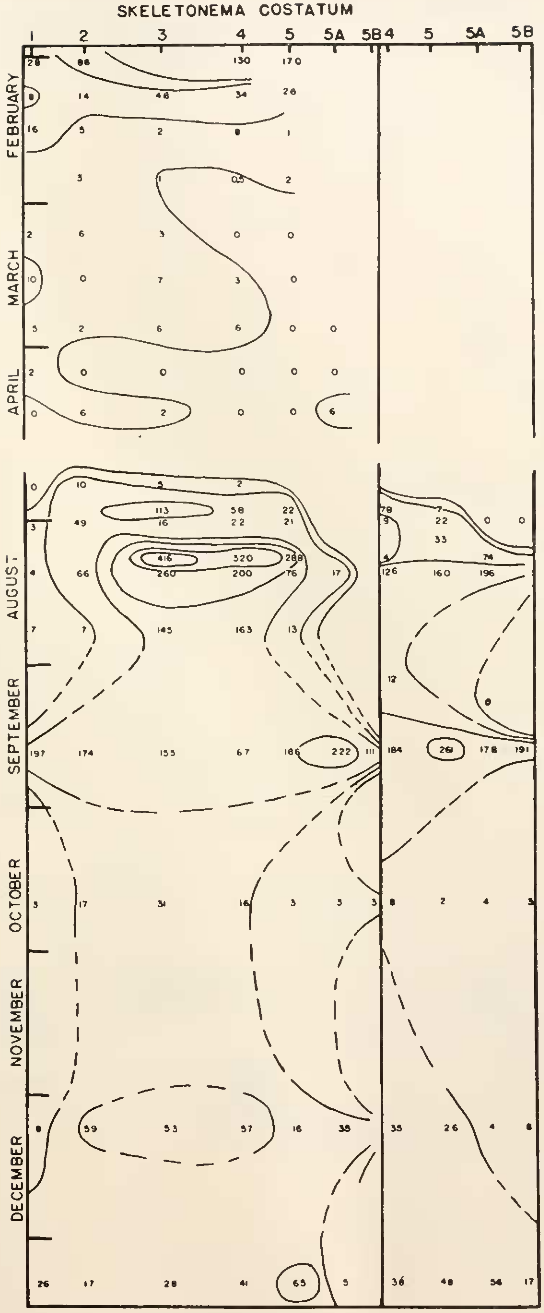

FIGURE 5. The distribution of *Skeletonema costatum*. Values $\times 10^5$ are numbers of cells per liter. Station numbers, 1–5b, cross the figure.

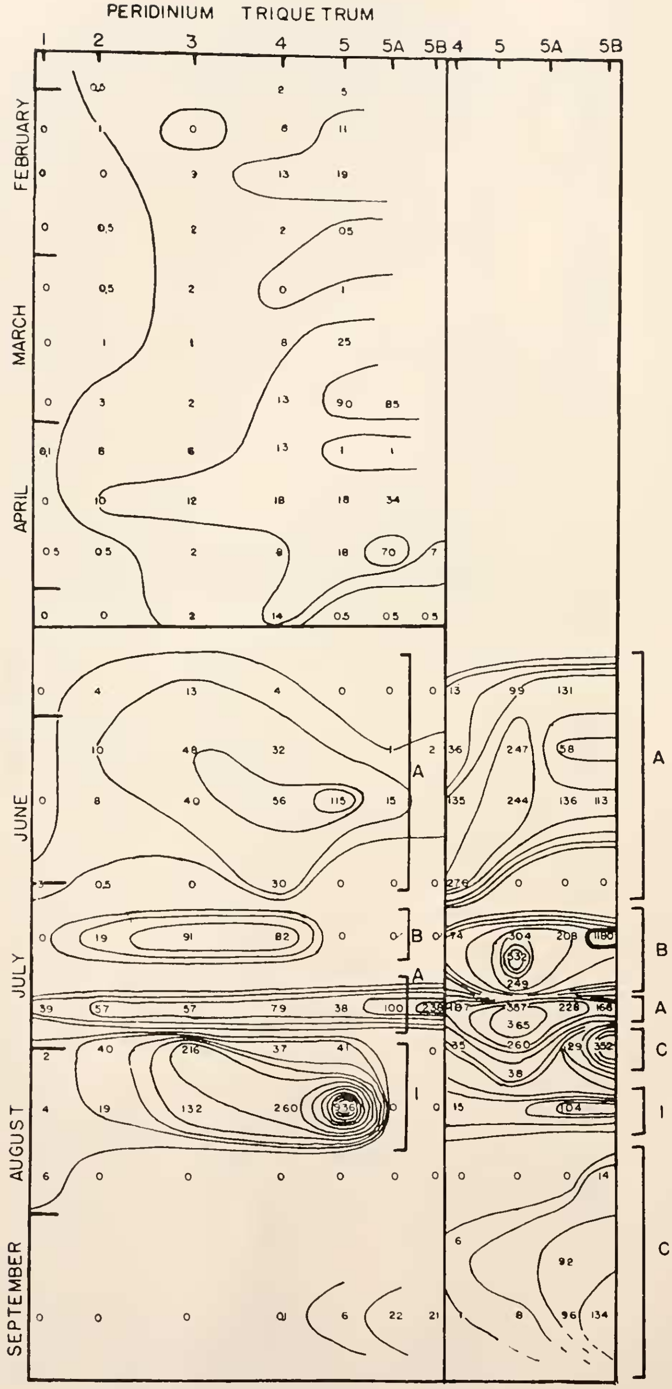
PERIDINIUM TRIQUETRUM
1
2
3
4
5
5A
5B
4
5
5A
5B
FEBRUARY
MARCH
APRIL
JUNE
JULY
AUGUST
SEPTEMBER
A
B
A
C
I
C

FIGURE 6.

larly noticeable in the surface waters of the arm, where isolated pools of high concentrations occurred on June 30 and on August 1, 11, and 23.

Cell concentrations along the bottom were, in a gross way, similar to those at the surface, being greater in summer than in fall or winter. However, with the exception of a brief period at the beginning of July, cell concentrations remained at high levels throughout the summer. The highest concentration observed, 120, 000,000 cells per liter, was at Station 5b, far from the Sound.

Seasonal cycles for several stations are shown in Figure 3. In the Sound there was a bimodal cycle, with moderate concentrations in late winter and spring and high concentrations in early fall. The surface waters of mid-pond showed a bimodal curve, also, with roughly the same concentrations in late winter and spring, as in the Sound, but, unlike the Sound, with very high concentrations in later summer. Deep water at mid-pond had high concentrations throughout summer and September and moderate concentrations in fall and winter. Sound and Pond both showed lowest concentrations at the end of May.

Figure 4 shows the distributions of three species of diatoms, *Leptocylindrus minimus, Nitzschia delicatissima,* and *Chaetoceros debilis.* These were observed only during the cooler months and were found to extend from the Sound far into the Pond. *Leptocylindrus minimus* showed a relatively uniform distribution in the Sound and seaward portion of the Pond. Though concentrations were occasionally somewhat greater in the Pond than in the Sound, they never showed a variation that was more than two-fold. In the surface waters of the arm concentrations were about the same as those in the seaward portion of the Pond on days of upwelling, March 26 and April 15, but were much lower on a normal day, April 5, when no upwelling occurred. In the Sound and main pond *Leptocylindrus minimus* increased rapidly to become the dominant species by February 15, attained a maximum on March 25, and decreased abruptly early in May. *Nitzschia delicatissima* showed a similar distribution to *Leptocylindrus minimus* during February. Its concentrations were about one-tenth those of *Leptocylindrus minimus. Chaetoceros debilis* resembled *Leptocylindrus* in distribution.

Skeletonema costatum, the distribution of which is shown in Figure 5, was the only species of diatom that was present during summer as well as during the rest of the year. At times it exhibited a uniform distribution from the Sound far into the Pond, as on September 18, January 10 and February 25. At various other times it was more abundant in the Pond than in the Sound, the variation being eight-fold on October 20, December 7 and January 30 and as high as one hundred-fold in August. During fall and winter it was the dominant species, attaining a maximum on September 18. In February it declined as *Leptocylindrus minimus* became the dominant species. Although *Skeletonema* was not clearly a dominant organism in August, it reached its greatest concentration at that time.

In spring the dinophycean *Peridinium triquetrum* rose to considerable prominence (see Figure 6), its concentrations being as high as one-fifth of those of *Leptocylindrus* on April 15. It was more abundant within the Pond than in the Sound. There was a hundred-fold increase from the Sound to the mid-reaches of

FIGURE 6. The distribution of Pond-derived species. Values $\times 10^5$ are numbers of cells per liter. Station numbers, 1–5b, cross the figure. A represents undetermined chrysophycean, B *Bipedinomonas pyriformis,* C *Nephrochloris salina,* and I *Chaetoceros simplex.*

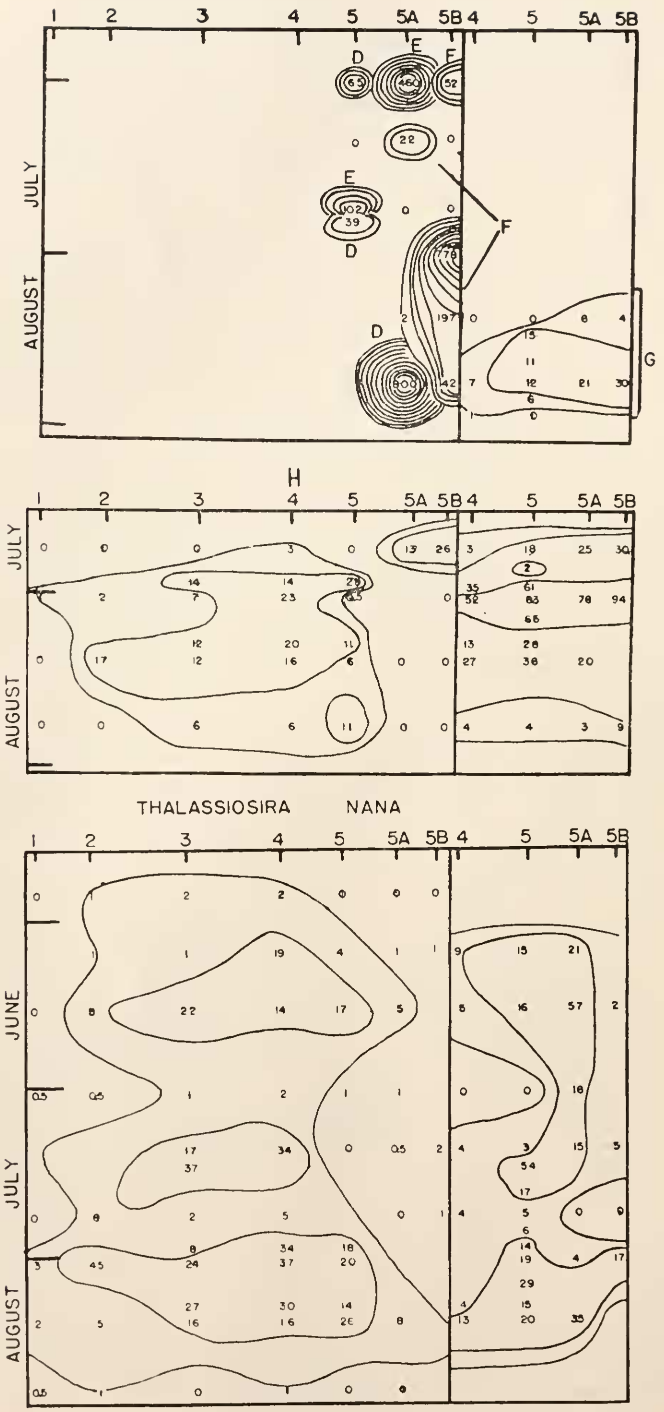
1 2 3 4 5 5A 5B 4 5 5A 5B
D
E
F
JULY
AUGUST
G
H
THALASSIOSIRA NANA
JUNE

FIGURE 7.

the Pond on March 26. This difference was greater than any observed for the four diatoms so far described in the period between mid-September and the end of May.

Figure 6 shows the distributions of several species found primarily in summer. They were always far more abundant in the Pond than in the Sound. During June the dominant species was an undetermined chrysophycean flagellate. Its numbers were usually greater along the bottom than at the surface. The surface waters at the ends of the Pond had smaller concentrations than the waters of mid-pond, the difference being as much as one hundred-fold. Only in mid-pond did concentrations approach those along the bottom. Abrupt decrease of the chrysophycean was followed in early July by a growth of the flagellate *Bipedinomonas pyriformis*. Its distribution was identical to that of the chrysophycean. By late July *Bipedinomonas* had disappeared completely and the undetermined chrysophycean flagellate was dominant again throughout the Pond. On July 22 the chrysophycean showed an exceptional abundance at the surface of the arm due to upwelling. In August the small diatom *Chaetoceros simplex* became extremely abundant, more so in the surface waters of mid-pond than in the deeper water. On August 11 it showed a two hundred-fold difference between Sound and Station 5. The flagellate *Nephrochloris salina* was moderately abundant in August and September in bottom water at the extreme landward end of the Pond.

Figure 7 shows the distributions of several less important species of summer. The flagellate *Gyrodinium estuariale* and the minute diatom *Thalassiosira nana* exhibited the same type of distribution as described for the undetermined chrysophycean. In the surface waters of the arm contours are close-packed around the flagellate *Chlamydomonas* in the surface waters at the outlet of the river and around the flagellates, *Massartia rotundata* and *Rhodomonas minuta,* farther down the arm. The growth of these species was sporadic and attained very great concentrations. It is noteworthy that when these species grew in the surface waters, no traces of the species were found in the bottom water only five or six feet below.

Discussion

The species can be divided into Sound-, Pond-, and River-derived types. The Sound-derived type was abundant in the Sound and Pond alike. The Pond-derived type was abundant only in the Pond, particularly in the inner reaches and along the bottom. The river type was found primarily in the surface water at the outlet of the River. The two principal Sound-type species were the diatoms *Leptocylindrus minimus* and *Skeletonema costatum. Nitzschia delicatissima* and *Chaetoceros debilis* represented well-defined Sound types, but were of minor importance. Principal Pond types were the undetermined chrysophycean flagellate; the heterokontan flagellate *Nephrochloris salina;* the chlorophycean flagellate *Bipedinomonas pyriformis;* the dinophycean flagellates *Peridinium triquetrum, Massartia rotundata,* and *Gyrodinium estuariale;* the cryptophycean flagellate *Rhodomonas minuta;* and the diatoms *Chaetoceros simplex* and *Thalassiosira nana.* The River type was repre-

FIGURE 7. The distribution of Pond- and River-derived species. Values $\times 10^5$ are numbers of cells per liter. Station numbers, 1–5b, cross the figure. D represents *Massartia rotunda,* E *Rhodomonas minuta,* F *Chlamydomonas* sp., G *Gyrodinium dominans,* and H *Gyrodinium estuariale.*

sented by chlorophycean flagellates, consisting of two unidentified species of *Chlamydomonas.*

The Sound-derived species thrived during fall, winter, and spring primarily and in summer to a small degree. The Pond-derived species flourished in summer primarily and in spring to a small degree. All of the Sound-derived forms were non-motile; the majority of the Pond-derived forms were motile.

During the fall, winter, and spring the water of the Sound, which fills 83% of the Pond at any time, carried its plankton far into the Pond. Within the estuary changes in this plankton were slight or negligible, indicated by the small difference in total plankton between Sound and Pond, by the change from dominance of *Skeletonema* to *Leptocylindrus* simultaneous in Sound and Pond, and finally by the intrusion of Sound species far into the Pond. During summer the Sound water carried with it little plankton, and once within the estuary the identity of this plankton was lost to a large degree. Plankton from the River could be identified only in the surface waters where the River emptied into the Pond. Throughout the greater portion of the Pond an indigenous plankton flourished.

TABLE I

Concentrations of diatoms and flagellates and statistics of physical features along the length of Great Pond

	Diatoms $\times 10^4/1$	Flagellates $\times 10^4/1$	Six-hour mean tidal velocity, knots	Salinity difference between surface and bottom, ‰
Sound	34	43	1.60	—
Mid-Pond, Station 4	633	598	0.01	6.38
Arm, Station 5a	319	1492	0.02	17.90

During the transport of water through the Pond, rapid changes in the plankton occurred in summer, as indicated by the abrupt changes in dominant species from place to place on the same survey. In the surface waters of the arm such changes caused large fluctuations in total phytoplankton. These changes indicate a rapid growth rate. During the remainder of the year abrupt changes in dominant species and extreme variations in total phytoplankton did not occur and hence growth rates were less than in summer. Thus, when conditions for growth in the Pond were good, Pond species rather than Sound species flourished. When growth conditions were less favorable, during the cool months, the plankton of the Sound drifted into the Pond, replacing the endemic flora that had previously flourished.

It has been pointed out that during summer the dominant members of the plankton included seven flagellates and three diatoms. In order to account for the preponderance of motile forms within the Pond, its association with low current velocities and great vertical stability of the water will be investigated. Averages of the dominant species as flagellates or diatoms are given for various stations in Table I. Surface and bottom values are averaged for stations 4 and 5a. Current velocities were taken from surface current measurements for Vineyard Sound one mile south of Great Pond (U. S. Coast and Geodetic Survey, 1949) and were computed for Great Pond by dividing the intertidal volume landward of a station by the cross-sectional area at the station. Surface current measurements may be higher than computed currents estimates by as much as 50% (Riley, 1952). The salinity difference between surface and bottom was the average difference of all observations during summer. Both diatoms and flagellates increased from the Sound to mid-pond, but flagellates increased at the expense of the diatoms from mid-pond to the headwaters. Tidal currents were much less from mid-pond to headwaters than in the Sound; while the vertical salinity gradient became progressively greater up-pond.

The moderate success of the motile cell from Sound to mid-pond can be attributed to a decrease in vertical turbulence, as a result of lessened tidal current. The greater success from mid-pond to the headwaters can be attributed to further decrease in turbulence, as a result of both weak currents and marked stability. Settling out of non-motile cells in the quiet waters of the Pond, particularly the arm, would place the motile cell at an advantage. In addition, cells destined to settle out would have less time to divide and replace the stock in the shallow waters of the Pond than in the deep waters of the Sound, so that the motile cell would be at a still greater advantage in the Pond. Thus, when growth conditions favor an endemic flora, the quietness and shoalness of the Pond water should favor motility as a characteristic of the flora.

The Pond flora may have been better adapted than the Sound flora to lowered salinity, high temperature, or nutrient products of the intermediate metabolism of the pond water. Adaptations of these sorts may have been effective in favoring the successive blooms of different species and in fostering the occasional dominance of non-motile forms.

In conclusion, the summer conditions at Great Pond furnish an example of the dominance of flagellates rather than diatoms in the phytoplankton. This dominance appears to result in part from a coupling of good growth conditions, which foster an endemic flora, with a quiet, very shallow habitat, which should favor the non-settling, motile cell.

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Summary

1. Determinations of phytoplankton concentrations were made throughout 1950 in Great Pond, a small estuary near Falmouth, Massachusetts.

2. Greater concentrations occurred within Great Pond than in the ocean water at its entrance. This difference was greatest in summer.

3. During fall, winter, and spring the same species populated the waters of the ocean and the Pond, but during the summer an assemblage of species flourished within the Pond that was never found in the ocean water and was not characteristic of the river water.

4. The Pond-derived flora of summer contained a large proportion of flagellates, whereas the Sound-derived flora was composed completely of diatoms.

5. The preponderance of motile forms within the Pond during summer was attributed to good growth conditions, which stimulated an endemic flora, and to shoal, quiet water, which should favor the non-settling type of cell.

LITERATURE CITED

BARLOW, J. The hydrography of Great Pond, a tidal estuary. *J. Mar. Res.*, in press.

BRAARUD, T., AND A. BURSA, 1939. The phytoplankton of the Oslo fjord, 1933–1934. *Det. Norske Vid. -Akad. i. Oslo, Hval. Scri.*, **19**: 1–63.

CONRAD, W., 1926a. Recherches sur les Flagellates de nos eaux saumâtres. Ie partie, Dinoflagellates. *Arch. f. Protist.*, **55**: 63–100.

CONRAD, W., 1926b. Recherches sur les Flagellates de nos eaux saumâtres. 2° partie, Chrysomonadines. *Arch. f. Protist.*, **56**: 167–231.

COWLES, R. P., 1930. A biological study of the offshore waters of Chesapeake Bay. *Bull. Bur. Fish.*, **46**: 277–381.

GRAN, H. H., AND T. BRAARUD, 1935. A quantitative study of the phytoplankton in the Bay of Fundy and the Gulf of Maine (including observations on hydrography, chemistry and turbidity). *J. Biol. Bd. Canada,* **1** (5) : 279–467.

LOHMANN, H., 1908. Untersuchungen zur Feststellung des vollständigen Gehaltes des Meeres an Plankton. *Wiss. Meeresunters. Abt. Kiel. N. F.*, **10**: 129–370.

MASSART, J., 1920. Recherches sur les organismes inférieurs, VIII. Sur la motilité des Flagellates. *Bull. Acad. Roy. Belgique, Cl. de Sc., 5me. Sér.* **6** (4–5) : 116–141.

MORSE, D. C., 1947. Some observations on seasonal variations in plankton population, Patuxent River, Maryland, 1943–1945. State of Maryland Board of Natural Resources. Pub. No. 65: 1–31.

RILEY, G. A., 1952. Hydrography of the Long Island and Block Island Sounds. *Bull. Bingham Oceano. Coll.*, **13** (3) : 5–39.

U. S. COAST AND GEODETIC SURVEY, 1949. Tidal Current Charts, Narragansett Bay to Nantucket Sound. Serial No. 628. Washington, D. C.

VAN GOOR, A. C. J., 1925a. Einige bemerkenswerte Peridineen des holländischen Brackwassers. *Rec. Trav. Bot. Néerl.*, **22**: 275–291.

VAN GOOR, A. C. J., 1925b. Die Euglenineae des holländischen Brachwassers mit besonderer Berücksichtigung ihrer Chromatophoren. *Rec. Trav. Bot. Néerl.*, **22**: 292–314.

VAN GOOR, A. C. J., 1925c. Über einige bemerkenswerte Flagellaten der holländischen Gewasser. *Rec. Trav. Bot. Néerl.*, **22**: 315–319.